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Strongly screened electron capture rates of chromium isotopes in presupernova evolution

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Abstract Taking into account the effect of electron screening on electron energy and electron capture threshold energy, by using the method of Shell-Model Monte Carlo and random phase approximation theory, we investigate the capture rates of chromium isotopes with strong electron screening according to the linear response theory screening model. Strong screening rates can decrease by about 40.43% (e.g., for ^{60}Cr at $T_9 = 3.44$, $Y_{\rm e} = 0.43$). Our conclusions may be helpful to researches on supernova explosions and related numerical simulation methods.

Key words: nuclear reactions — electron capture — supernovae

1 INTRODUCTION

At the presupernova stage, beta decay and electron capture (EC) on some neutron-rich nuclei may play important roles in determining the hydrostatic core structure of massive presupernova stars, thereby affecting their subsequent evolution during the gravitational collapse and supernova explosion phases (e.g., Dean et al. 1998; Caurier et al. 1999; Juodagalvis et al. 2010; Liu 2013, 2014; Liu et al. 2016; Liu & Gu 2016; Liu et al. 2017). For example, beta decay (EC) strongly influences the time rate of change of the lepton fraction (e.g., the time rate of change of electron fraction $\dot{Y}_{\rm e}$) by increasing (decreasing) the number of electrons. Some isotopes of iron, chromium and copper can also make a substantial contribution to the overall changes in lepton fraction (e.g., $\dot{Y}_{\rm e}$), electron degeneracy pressure and entropy of the stellar core during its very late stage of evolution. Many of these nuclei can be appropriately tracked in the reaction network of stellar evolution calculations. The lepton fraction (e.g., $\dot{Y}_{\rm e}$) is bound to lead to an unstoppable process of gravitational collapse and supernova explosion.

Some research has shown that EC in iron group nuclei (e.g., iron and chromium isotopes) is a very important and dominant process in supernova explosions (e.g., Aufderheide et al. 1990, 1994; Dean et al. 1998; Heger et al. 2001). In the process of presupernova evolution, chromium isotopes are a very important and crucial radionuclide. Aufderheide et al. (1994) investigated EC and beta decay for these nuclei in detail in presupernova evolution. They found that the EC rates of these chromium isotopes can be of significant astrophysical importance by controlling the electronic abundance. Heger et al. (2001) also discussed weak-interaction rates for some iron group nuclei by employing shell model calculations in presupernova evolution. They found that EC rates on iron group nuclei would be crucial for decreasing the electronic abundance ($Y_{\rm e}$) in stellar matter.

On the other hand, in the process of presupernova evolution in massive stars, the Gamow-Teller (GT) transitions of isotopes of chromium play a consequential role. Some studies have shown that β-decay and EC rates of chromium isotopes significantly affect the time rate of change of lepton fraction ($\dot{Y}_{\rm e}$). For example, Nabi et al. (2016) detailed the GT strength distributions, $\dot{Y}_{\rm e}$ and neutrino energy loss rates for chromium isotopes due to weak interactions in stellar matter.

However, their works did not discuss the problem of how strong electron screening (SES) would effect EC. What role does EC play in stellar evolution? How does SES influence the EC reaction at high density and temperature? In order to accurately calculate the EC rates and screening correction for numerical simulations of supernova explosions, in this paper we will discuss this problem in detail.

Based on the linear response theory model (LRTM) and random phase approximation (RPA), we study strongly screened EC rates of chromium isotopes in astrophysical environments by using the Shell-Model Monte Carlo (SMMC) method. In the next section, we discuss the methods used for EC in stellar interiors in the cases with and without SES. Section 3 will present some numerical results and discussions. Conclusions follow in Section 4.

2 EC RATES IN THE PROCESS OF STELLAR CORE COLLAPSE

2.1 EC Rates in the Case without SES

For nucleus (Z, A), we calculate the stellar EC rates, which are given by a sum over the initial parent states i and the final daughter states f at temperature T. This expression is written as (e.g., Fuller et al. 1980, 1982)

$$\lambda_k = \sum_i \frac{(2J_i+1)e^{\frac{-E_i}{kT}}}{G(Z,A,T)} \sum_f \lambda_{if}, \tag{1}$$

where J_i is the spin and E_i is excitation energies of the parent states. The nuclear partition function $G(Z, A, T)$ has been discussed by Aufderheide et al. (1990, 1994). λ_{if} denotes the rates from one of the initial states to all possible final states.

Based on the theory of RPA, the EC rates are closely related to cross section $\sigma_{\rm ec}$, and can written as (e.g., see detailed discussions in Dean et al. 1998; Caurier et al. 1999; Juodagalvis et al. 2010)

$$\begin{aligned}\lambda_{if} &= \frac{1}{\pi^2\hbar^3}\sum_{if}\int_{\varepsilon_0}^{\infty} p_{\rm e}^2\sigma_{\rm ec}(\sigma_{\rm e},\sigma_i,\sigma_f) \\ &\quad f(\sigma_{\rm e},U_F,T)d\varepsilon_{\rm e}\end{aligned} \tag{2}$$

where $\varepsilon_0 = \max(Q_{if}, 1)$. The incoming electron momentum is $p_{\rm e} = \sqrt{\varepsilon_{\rm e} - 1}$, $\varepsilon_{\rm e}$ is the electron energy, the electron chemical potential is given by U_F and T is the electron temperature. The energies and momenta are in units of $m_{\rm e}c^2$ and $m_{\rm e}c$ respectively ($m_{\rm e}$ is the electron mass and c is the speed of light).

The electron chemical potential is obtained by

$$n_{\rm e} = \frac{\rho}{\mu_{\rm e}} = \frac{8\pi}{(2\pi)^3}\int_0^{\infty} p_{\rm e}^2(G_{-e} - G_{+e})dp_{\rm e}, \tag{3}$$

where $\mu_{\rm e}$ and ρ are the average molecular weight and the density in $\rm g\,cm^{-3}$, respectively. $\lambda_{\rm e} = \frac{h}{m_{\rm e}c}$ is the Compton wavelength, $G_{-e} = [1+\exp(\frac{\varepsilon_{\rm e}-U_F-1}{kT})]^{-1}$ and $G_{+e} = [1+\exp(\frac{\varepsilon_{\rm e}+U_F+1}{kT})]^{-1}$ are the electron and positron distribution functions respectively, and k is the Boltzmann constant. The phase space factor is defined as

$$f(\varepsilon_{\rm e}, U_F, T) = \left[1+\exp\left(\frac{\varepsilon_{\rm e}-U_F}{kT}\right)\right]^{-1}. \tag{4}$$

According to energy conservation, the electron, proton and neutron energies are related to the neutrino energy, and the Q-value for the capture reaction is (Cooperstein & Wambach 1984)

$$Q_{if} = \varepsilon_{\rm e} - \varepsilon_\nu = \varepsilon_n - \varepsilon_\nu = \varepsilon_f^n - \varepsilon_i^p, \tag{5}$$

so we have

$$\varepsilon_f^n - \varepsilon_i^p = \varepsilon_{if}^* + \hat{\mu} + \Delta_{np}, \tag{6}$$

where ε_ν is neutrino energy, ε_i^p is the energy of an initial proton single particle state and ε_f^n is the energy of a neutron single particle state. $\hat{\mu} = \mu_n - \mu_p$ and $\Delta_{np} = M_nc^2 - M_pc^2 = 1.293\,$MeV are the chemical potential and mass difference between a neutron and proton in the nucleus, respectively. $Q_{00} = M_fc^2 - M_ic^2 = \hat{\mu} + \Delta_{np}$, and the masses of the parent nucleus and daughter nucleus correspond to M_i and M_f respectively; ε_{if}^* is the excitation energies for the daughter nucleus at zero temperature.

The total cross section in the process of EC reaction is given by (e.g., Dean et al. 1998; Caurier et al. 1999; Juodagalvis et al. 2010)

$$\begin{aligned}\sigma_{\rm ec} &= \sigma_{\rm ec}(\varepsilon_{\rm e}) \\ &= \sum_{if}\frac{(2J_i+1)\exp(-\beta\varepsilon_i)}{Z_A}\sigma_{fi}(\varepsilon_{\rm e}) \\ &= 6g_{\rm wk}^2\int d\xi(\varepsilon_{\rm e}-\xi)^2\frac{G_A^2}{12\pi}S_{\rm GT^+}(\xi) \\ &\quad F(Z,\varepsilon_{\rm e})\end{aligned} \tag{7}$$

where $g_{\rm wk} = 1.1661\times10^{-5}\,\rm GeV^{-2}$ is the weak coupling constant and $G_A = 1.25$. $F(Z, \varepsilon_{\rm e})$ is the factor for Coulomb wave correction.

The total amount of GT strength is $S_{\rm GT^+}$, which is calculated by summing over a complete set from an initial state to final states. The response function $R_A(\tau)$ of an operator $\hat{A}$ at an imaginary time τ is calculated by using the method of SMMC. Thus, $R_A(\tau)$ is given by (e.g., Dean et al. 1998; Juodagalvis et al. 2010)

$$R_A(\tau) = \frac{\sum_{if}(2J_i+1)e^{-\beta\varepsilon_i}e^{-\tau(\varepsilon_f-\varepsilon_i)}|\langle f|\hat{A}|i\rangle|^2}{\sum_i(2J_i+1)e^{-\beta\varepsilon_i}}. \tag{8}$$

The strength distribution is related to $R_A(\tau)$ by a Laplace transform $R_A(\tau) = \int_{-\infty}^{\infty} S_A(\varepsilon)e^{-\tau\varepsilon}d\varepsilon$ and is given by (e.g., Dean et al. 1998; Caurier et al. 1999; Juodagalvis et al. 2010)

$$S_{\mathrm{GT}^+}(\varepsilon) = S_A(\varepsilon) = \frac{\sum_{if} \delta(\varepsilon - \varepsilon_f + \varepsilon_i)(2J_i+1)e^{-\beta\varepsilon_i}|\langle f|\hat{A}|i\rangle|^2}{\sum_i (2J_i+1)e^{-\beta\varepsilon_i}} \quad (9)$$

where ε is the energy transfer within the parent nucleus, the $S_{\mathrm{GT}^+}(\varepsilon)$ is in units of MeV^{-1}, $\beta = \frac{1}{T_N}$ and T_N is the nuclear temperature.

For degenerate relativistic electron gas, the EC rates in the case without SES are given by (e.g., Dean et al. 1998; Caurier et al. 1999; Juodagalvis et al. 2010)

$$\lambda^0_{\mathrm{ec}} = \frac{\ln 2}{6163}\int_0^\infty d\xi S_{\mathrm{GT}^+}\frac{c^3}{(m_{\mathrm{e}}c^2)^5}\int_{p_0}^\infty dp_{\mathrm{e}}p_{\mathrm{e}}^2 (-\xi+\varepsilon_{\mathrm{e}})^2 F(Z,\varepsilon_{\mathrm{e}})f(\varepsilon_{\mathrm{e}},U_F,T). \quad (10)$$

The p_0 is defined as

$$p_0 = \begin{cases} \sqrt{Q_{if}^2 - 1} & (Q_{if} < -1) \\ 0 & (\text{otherwise}). \end{cases} \quad (11)$$

2.2 EC Rates in the Case with SES

In 2002, based on the LRTM for relativistic degenerate electrons, Itoh et al. (2002) discussed the effect of screening potential on EC. The electron is strongly degenerate in our considered regime of density-temperature. This condition is expressed as

$$T \ll T_{\mathrm{F}} = 5.930\times 10^9\left\{\left[1+1.018\left(\frac{Z}{A}\right)^{2/3}(10\rho_7)^{2/3}\right]^{1/2} - 1\right\}, \quad (12)$$

where T_{F} and ρ_7 are the electron Fermi temperature and density (in units of $10^7\,\mathrm{g\,cm^{-3}}$).

For a relativistically degenerate electron liquid, Jancovici (1962) studied the static longitudinal dielectric function. Taking into account the effect of strong screening, the electron potential energy is written as

$$V(r) = -\frac{Ze^2(2k_{\mathrm{F}})}{2k_{\mathrm{F}}r}\frac{2}{\pi}\int_0^\infty \frac{\sin\left[\left(2k_{\mathrm{F}}r\right)\right]q}{q\epsilon(q,0)}dq, \quad (13)$$

where $\epsilon(q,0)$ is Jancovici's static longitudinal dielectric function and k_{F} is the electron Fermi wave-number.

The screening potential for relativistic degenerate electrons from linear response theory is written as (Itoh et al. 2002)

$$D = 7.525\times 10^{-3}Z\left(\frac{10z\rho_7}{A}\right)^{\frac{1}{3}}J(r_{\mathrm{s}},R)\ \ (\mathrm{MeV}). \quad (14)$$

Itoh et al. (2002) discussed the parameters $J(r_{\mathrm{s}},R)$, r_{s} and R in detail. Equation (14) is fulfilled in a presupernova environment and is satisfied for

$$10^{-5} \le r_{\mathrm{s}} \le 10^{-1}, \qquad 0 \le R \le 50.$$

The screening energy is sufficiently high that we cannot neglect its influence at high density when electrons are strongly screened. The electron screening will make electron energy decrease from ε to $\varepsilon' = \varepsilon - D$ in the process of EC. Meanwhile, the screening relatively increases threshold energy from ε_0 to $\varepsilon_{\mathrm{s}} = \varepsilon_0 + D$ for EC. So, the EC rates in SES are given by (e.g., Juodagalvis et al. 2010; Liu 2014)

$$\lambda^s_{\mathrm{ec}} = \frac{\ln 2}{6163}\int_0^\infty d\xi S_{\mathrm{GT}^+}\frac{c^3}{\left(m_{\mathrm{e}}c^2\right)^5}\int_{\varepsilon_{\mathrm{s}}}^\infty d\varepsilon'\varepsilon'(\varepsilon'^2-1)^{\frac{1}{2}}(-\xi+\varepsilon')^2 F(Z,\varepsilon')f(\varepsilon_{\mathrm{e}},U_F,T). \quad (15)$$

The nuclear binding energy will increase due to interactions with the dense electron gas in the plasma. The effective nuclear Q-value (Q_{if}) will change at high density due to the influence of the charge dependence on this binding. When we take the effect of SES into account, the EC Q-value will increase by (Fuller et al. 1982)

$$\Delta Q \approx 2.940\times 10^{-5}Z^{2/3}(\rho Y_{\mathrm{e}})^{1/3}\quad \mathrm{MeV}. \quad (16)$$

Therefore, the Q-value of EC increases from Q_{if} to $Q'_{if} = Q_{if} + \Delta Q$. The ε_{s} is defined as

$$\varepsilon_{\mathrm{s}} = \begin{cases} Q'_{if} + D & (Q'_{if} < -m_{\mathrm{e}}c^2) \\ m_{\mathrm{e}}c^2 + D & (\text{otherwise}). \end{cases} \quad (17)$$

We define the screening enhancement factor C to enable a comparison of the results as follows

$$C = \frac{\lambda^s_{\mathrm{ec}}}{\lambda^0_{\mathrm{ec}}}. \quad (18)$$

3 NUMERICAL CALCULATIONS OF EC RATES AND DISCUSSION

The influences of SES on EC rates for these chromium isotopes at some typical astrophysical conditions are shown in Figure 1. Note that the no SES and SES rates correspond to solid and dotted lines respectively. We give details about the EC process according to the SMMC method, especially for the contribution to EC due to the GT transition. For a given temperature, the EC rates increase by more than six orders of magnitude as the density increases. Based on the proton-neutron quasiparticle

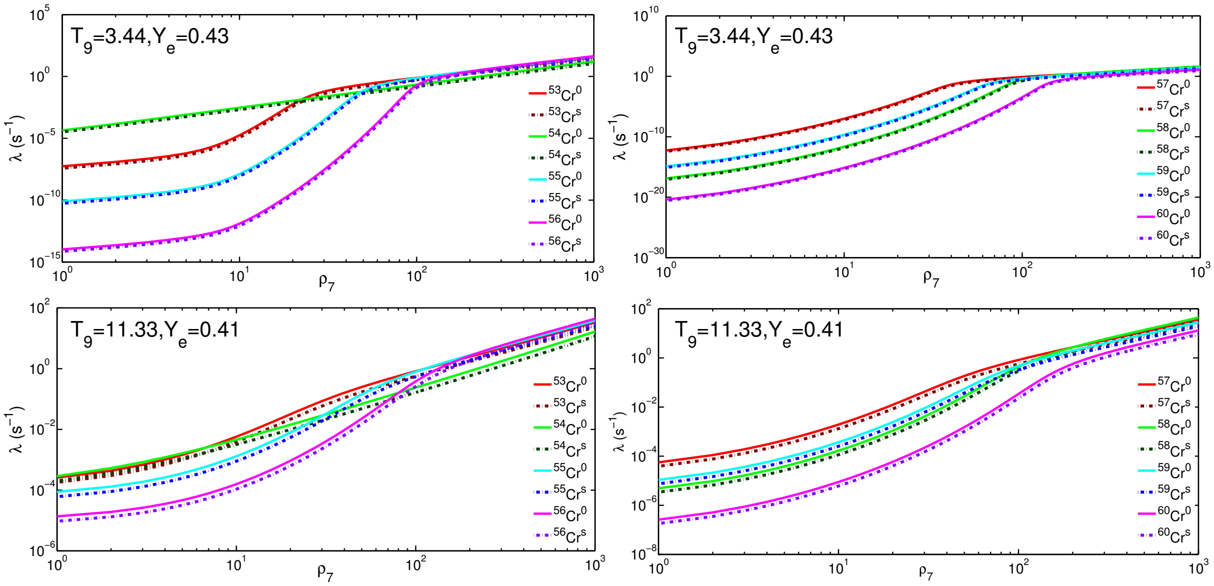

Fig. 1 The no SES and SES rates correspond to solid and dotted lines respectively for chromium isotopes as a function of density ρ_7 at temperatures of $T_9 = 3.44, Y_\mathrm{e} = 0.43$ and $T_9 = 11.33, Y_\mathrm{e} = 0.41$.

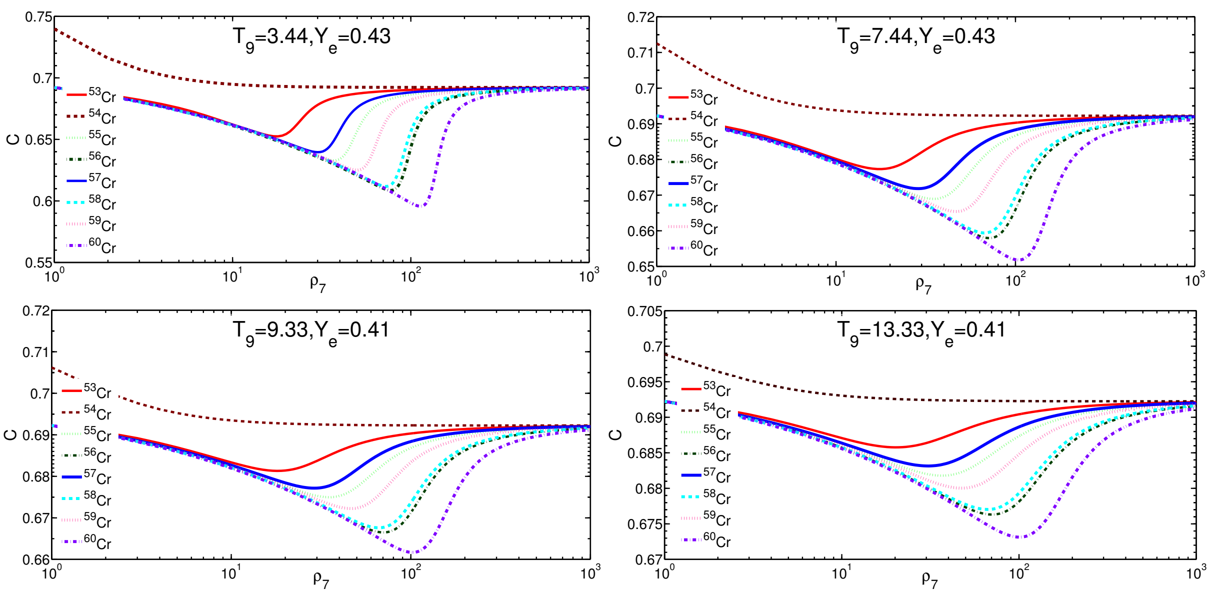

Fig. 2 The SES enhancement factor C for chromium isotopes as a function of the density ρ_7 at temperatures of $T_9 = 3.44, 7.44, Y_\mathrm{e} = 0.43$ and $T_9 = 9.33, 11.33, Y_\mathrm{e} = 0.41$. Four different line styles correspond to $^{53-56}\mathrm{Cr}$. The same line styles also correspond to $^{57-60}\mathrm{Cr}$. But the latter is far coarser than the former.

RPA (pn-QRPA) model, Nabi & Klapdor-Kleingrothaus (NKK) also investigated the EC rates in detail in the case without SES. Their results also showed that density strongly influences the EC rates for a given temperature. For example, the EC rate for $^{61}\mathrm{Cr}$ increases from $6.3096 \times 10^{-23}\ \mathrm{s}^{-1}$ to $3.71535 \times 10^{2}\ \mathrm{s}^{-1}$ when the density changes from $10^7\,\mathrm{g\,cm^{-3}}$ to $10^{11}\,\mathrm{g\,cm^{-3}}$ at $T_9 = 3$ (see the detailed discussions in Nabi & Klapdor-Kleingrothaus 1999). Under the same conditions, the Fuller, Fowler & Newman rate for $^{60}\mathrm{Cr}$ increases from $8.3946 \times 10^{-26}\,\mathrm{s}^{-1}$ to $1.2388 \times 10^{3}\,\mathrm{s}^{-1}$ (see Fuller et al. 1982). These studies demonstrate that the stellar weak rates play a key role in the dynamics of core collapse calculations and stellar numerical simulation.

According to our calculations, the GT transition EC reaction may not be the dominant process at lower tem-

Table 1 Comparison of our results by SMMC for total strength, centroid and width of calculated GT strength distributions with those of NKK (Nabi et al. 2016) for EC of $^{53-60}$Cr.

	$\sum \mathrm{B(GT)}_+$		E_+(MeV)		Width_+ (MeV)	
Nuclide	NKK	SMMC	NKK	SMMC	NKK	SMMC
^{53}Cr	0.51	0.5625	6.21	6.334	2.72	2.813
^{54}Cr	1.95	2.2340	2.88	2.912	3.32	3.406
^{55}Cr	0.39	0.4130	4.06	4.126	3.47	3.675
^{56}Cr	1.31	1.3326	1.77	1.791	2.14	2.366
^{57}Cr	0.25	0.2740	5.21	5.267	2.84	2.972
^{58}Cr	0.82	0.8411	1.57	1.605	2.49	2.560
^{59}Cr	0.24	0.2520	1.26	1.302	2.24	2.272
^{60}Cr	0.39	0.4012	3.03	3.201	4.99	5.017

perature. On the other hand, the higher the temperature is, the larger the electron energy, the larger the density and the higher the electron Fermi energy become. Therefore, a lot of electrons join in the EC reaction and the GT transition would be very active and be the dominant contribution to the total EC rates. Figure 1 displays the screening rates and no screening rates, which correspond to solid and dotted lines respectively as a function of density. We find that the screening rates are commonly lower than no screening rates.

The GT strength distributions play a significant role in supernova evolution. However, the GT$^+$ transitions are addressed only qualitatively in presupernova simulations because of insufficient experimental information. The general rule is that the energy for the daughter ground state is parameterized phenomenologically by assuming the GT$^+$ strength resides in a single resonance. Charge exchange reactions (n, p) and (p, n) would, if obtainable, supply us with plenty of experimental information. However, any available experimental GT+ strength distributions for these nuclei cannot be obtained except for theoretical calculations.

Table 1 presents a comparison of our results by SMMC for total strength, centroid and width of calculated GT strength distributions with those of NKK (Nabi et al. 2016) for EC of $^{53-60}$Cr. Our results of calculated GT strength distributions are higher than those of NKK.

Based on pn-QRPA theory, NKK analyzed the nuclear excitation energy distribution by taking into consideration particle emission processes. They calculated a stronger GT strength distribution from these excited states compared to those assumed using Brink's hypothesis. However, in their works, they only discussed the low angular momentum states. By using the method of SMMC, the GT intensity distribution is discussed in detail and an average value of the distribution is actually adopted in our paper.

Values for the screening factor C are plotted as a function of ρ_7 in Figure 2. Due to SES, the rates decrease by about 40.43%. The lower the temperature, the larger the effect of SES on EC rates is. This is due to the fact that SES mainly decreases the number of higher energy electrons which can actively join in the EC reaction. Moreover, the SES can also make the EC threshold energy increase greatly. As a matter of fact, SES will strongly weaken the progress of EC reactions. One can also find that the screening factor almost tends to the same value at higher density and it is not dependent on the temperature or density. The reason is that at higher density the electron energy is mainly determined by its Fermi energy, which is strongly decided by density.

Table 2 shows details about the numerical calculations of minimum values for screening factor $C_{\min}$. One finds that the EC rates decrease greatly due to SES. For instance, from Table 2 that provides values for the factor $C_{\min}$, the rates decrease about 34.75%, 30.77%, 36.92%, 39.07%, 35.98%, 38.81%, 37.50% and 40.43% for $^{53-60}$Cr at $T_9 = 3.44, Y_\mathrm{e} = 0.43$. This is due to the fact that the SES mainly decreases the number of higher energy electrons, which can actively join in EC reactions. On the other hand, the screening of nuclear electric charges with a high electron density means a short screening length, which results in a lower enhancement factor from Coulomb wave correction. However, even a relatively short electric charge screening length will not have much effect on the overall rate due to the weak interaction being effectively a contact potential. A bigger effect is that electrons are bound in the plasma.

Synthesizing the above analysis, the effects of charge screening on nuclear physics (e.g., EC and beta decay) come at least from the following factors. First, the screening potential will change the electron Coulomb wave function in nuclear reactions. Second, the electron screening potential decreases the energy of inci-

Table 2 The Minimum Values of Strong Screening Factor C for Some Typical Astronomical Conditions when $1 \leq \rho_7 \leq 10^3$

	$T_9 = 3.44, Y_e = 0.43$		$T_9 = 7.44, Y_e = 0.43$		$T_9 = 9.33, Y_e = 0.41$		$T_9 = 13.33, Y_e = 0.41$	
Nuclide	ρ_7	$C_{\min}$	ρ_7	$C_{\min}$	ρ_7	$C_{\min}$	ρ_7	$C_{\min}$
^{53}Cr	18	0.6525	19	0.6774	19	0.6813	20	0.6858
^{54}Cr	62	0.6923	65	0.6924	66	0.6924	67	0.6924
^{55}Cr	38	0.6308	37	0.6690	36	0.6750	37	0.6818
^{56}Cr	81	0.6093	72	0.6580	71	0.6665	71	0.6763
^{57}Cr	32	0.6402	30	0.6719	31	0.6772	33	0.6832
^{58}Cr	74	0.6119	69	0.6594	67	0.6676	67	0.6770
^{59}Cr	50	0.6250	47	0.6654	49	0.6723	48	0.6800
^{60}Cr	115	0.5957	106	0.6518	104	0.6617	99	0.6731

dent electrons joining in the capture reactions. Third, the electron screening increases the energy of atomic nuclei (i.e., increases the single particle energy) in nuclear reactions. Finally, the electron screening effectively decreases the number of higher-energy electrons, whose energy is more than the threshold of the capture reaction. Therefore, screening relatively increases the threshold needed for capture reactions and decreases the capture rates.

4 CONCLUDING REMARKS

In this paper, based on the theory of RPA and LRTM and by using the method of SMMC, we investigate the EC rates in SES. The EC rates increase greatly by more than six orders of magnitude as the density increases. On the other hand, by taking into account the influence of SES on the energy of incident electrons and threshold energy of EC, the EC rates decrease by $\sim 40.43\%$.

ECs play an important role in the dynamic process of the collapsing core of a massive star. It is a main parameter for supernova explosion and stellar collapse. SES strongly influences EC and may influence the cooling rate and evolutionary timescale of stellar evolution. Thus, the conclusions we obtained may have a significant influence on further research of supernova explosions and related numerical simulations.

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